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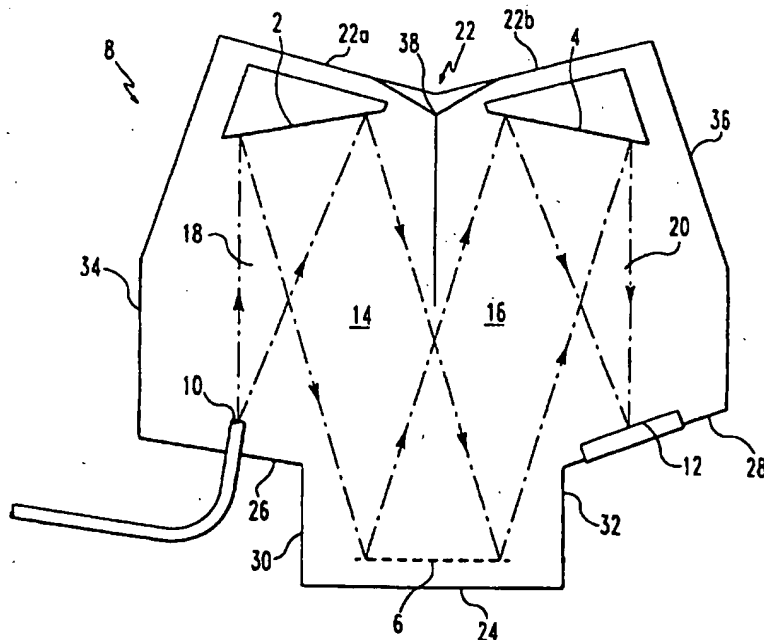
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(71) Applicant (for all designated States except US): DIASENSE, INC. [US/US]; The Bourse, Building 2500, 2nd floor, 2275 Swallow Hill Road, Pittsburgh, PA 15220 (US).			
(72) Inventors; and (75) Inventors/Applicants (for US only): RABER, Peter, E. [US/US]; 26 Dawn Drive, Indiana, PA 15701 (US). SANTMAN, Jeff [US/US]; 9 Gatewood Road, Levittown, PA 19057 (US).			
(74) Agents: BYRNE, Richard, L. et al.; Webb Ziesenheim Bruening Logsdon Orkin & Hanson, P.C., 700 Koppers Building, 436 Seventh Avenue, Pittsburgh, PA 15219-1818 (US).			

(54) Title: METHODS AND APPARATUS FOR NON-INVASIVE GLUCOSE SENSING: SPECTROGRAPH

(57) Abstract

A spectrograph designed for the near-infrared spectral region is described for use in a non-invasive sensor for measuring glucose levels in the human body. The spectrograph includes optical converging means (2, 4) and dispersive means (6) mounted and combined with source means (10) and detection means (12). The source means can be a linear input array of optical fibers and the detection means can be a multi-element detector array with long, narrow pixels. Filtered light that has passed through human tissue and, therefore, contains a unique spectral absorption signature, is transmitted to the fiber array of the spectrograph. The radiation is then dispersed into constituent spectral components, each of which is sent to a different pixel of the detector array. The differing signals produced at each pixel are then analyzed to discern the glucose level in the tissue.



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METHODS AND APPARATUS FOR NON-INVASIVE
GLUCOSE SENSING: SPECTROGRAPH

BACKGROUND OF THE INVENTION

1. Field of the Invention

5 This invention relates to a spectrograph suitable for use in the non-invasive sensing of blood glucose levels.

2. Background of the Art

10 It is generally known in the art that radiation, particularly near-infrared radiation over a range of wavelengths, can be projected on a portion of the body of a patient and that the resulting radiation emitted from that portion of the body, either scattered or transmitted after absorption and scattering, can be detected and
15 processed to derive an expression of the resulting radiation as a function of wavelength and, therefrom, the concentration of blood glucose. See, for example, United States Patent No. 5,070,874 to Barnes et al. Since the detected radiation is a continuous signal covering all of
20 the wavelengths in the range of interest, it is necessary for further analysis to separate the intensities of radiation at the various wavelengths, or smaller bands of wavelengths, in the range in order to extract the desired blood glucose level information.

25 It is known in the art that a spectroscope, including an input slit, a collimator lens, a prism or grating and an objective lens, can produce the desired spectrum of intensities versus wavelength for visual observation. A spectrograph includes a camera or the like
30 for recording the spectrum generated by a spectroscope. A well-known arrangement for a spectroscope is the Czerny-Turner arrangement which includes an input slit projecting radiation in a generally conical beam to a collimator mirror which, in turn, projects a collimated radiation beam
35 to a diffraction grating which separates the radiation into various wavelengths or bands of wavelengths and transmits the generated spectrum in a collimated beam to an image mirror which passes a generally conical beam to an output slit for observation, recordation and analysis.

Prior art spectrometers generally employ fixed input slits and output slits. Radiation from the input slit is dispersed over a wide area in the focal region of the input mirror, and only a small portion of this radiation is detected through the output slit. In prior art spectrographs, either this output slit may be moved to map the area of dispersion, or the dispersive element, i.e., the diffraction grating, or other optical component may be moved to achieve this mapping, or a photographic film or plate may replace the output slit to record the spectrum for later study and analysis. In addition, prior art spectrometers typically require many degrees of alignment freedom for all optical components, so that each can be optimally aligned and focused for best performance in painstaking, labor-intensive operations.

SUMMARY OF THE INVENTION

Accordingly, we have developed a spectrograph which is particularly suitable for use in the non-invasive sensing of glucose concentrations in the body of a patient. The spectrograph includes a collimating input mirror, a focusing output mirror and a dispersive element positioned in an enclosure in a Czerny-Turner type of arrangement. The input mirror and the output mirror are attached to a first sidewall of the enclosure and form a converging means having intersecting regions of substantial collimation located substantially at the dispersive element. In addition, the dispersive element is attached to a second sidewall of the enclosure generally opposite the first sidewall. The spectrograph also includes a fiber array positioned at an input location in the enclosure and directing radiation toward the input mirror. The fiber array carries radiation from the patient after irradiation with radiation over a predetermined range of wavelengths. The spectrograph also includes a detector array positioned at an output location in the enclosure and oriented to receive radiation from the output mirror. The detector array includes a plurality of photodetector elements and

each element detects a different wavelength region of the radiation. A plane common to the elements of the detector array is tilted with respect to a central ray emanating from the output mirror. The input mirror and the output
5 mirror are each formed as off-axis, substantially parabolic and substantially identical mirrors. The radiation is preferably in the near-infrared spectral region. The combination of the off-axis parabolic input and output mirrors and the tilt of the detector array produces a wide
10 optical field of view at the detector array.

The present invention incorporates a wide-area detector array in the focal region of the output mirror, and this detector array simultaneously records the equivalent of many such output slits in a real-time manner.
15 This simultaneous recording in a real-time manner allows near-simultaneous electronic data integration, manipulation and recordation of the spectral signature of the input radiation. The reflective optics, i.e., input and output mirrors, produce high-throughput (near zero absorbance)
20 astigmatic imaging through the wide-angle focal region of the detector array. The astigmatic imaging is particularly compatible with the multi-slit nature of the detector array. The off-axis parabolic mirrors preferably have integral rear mounting surfaces normal to the focused beam
25 axis, rather than to the parabolic axis, as is common with such mirror types. This feature provides rapid alignment and focusing capability for high volume manufacturability of the device. The mounting configuration of the off-axis parabolic mirrors is also designed to be inversely
30 symmetrical, and the spectrograph is designed to operate at unity magnification between the input and the output. These features allow the input and output mirrors to be identical mechanically as well as optically, so that they can be used interchangeably in either the input or source
35 region, or the output or camera region. This interchangeability of mirrors helps to prevent assembly errors and substantially reduces production tooling and

inventory costs in high volume manufacturing. The design of the present invention in a preferred embodiment also permits rapid alignment with minimal adjustability of each component in an arrangement suitable for moderate
5 resolution and high production volumes.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a top plan view of a schematic diagram of a spectrograph in accordance with the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

10 A preferred embodiment of a spectrograph in accordance with the present invention is shown in FIG. 1 in plan view. The spectrograph includes a collimating input or source mirror 2, a focusing output or camera mirror 4 and a dispersive element 6, such as a diffraction grating,
15 positioned within a surrounding enclosure 8 in a Czerny-Turner type of arrangement. The view shown in FIG. 1 is looking down on the spectrograph with the lid or closure for the enclosure 8 removed. The elements of the spectrograph would, in operation, be enclosed by the
20 sidewalls visible in FIG. 1 as well as by a lid and bottom tightly attached to the sidewalls. In accordance with the present invention, the Czerny-Turner type of spectrometer has its ordinary input slit replaced by a fiber array 10 including a linear array of optical fibers. An extended
25 output area is occupied by a detector array 12, which is sensitive throughout a wide near-infrared spectral region, rather than a simple output slit as in many standard spectrometers. The preferred embodiment of the present invention uses off-axis parabolic mirrors for the input
30 mirror 2 and the output mirror 4 which, together, form an optical converging means. The preferred embodiment of the present invention also uses a blazed diffraction grating as the dispersive element 6.

35 The numerical aperture of the optical fibers in the fiber array 10 and the optics in the spectrograph must be compatible in that the output of the fiber array 10 should fill or overfill the input mirror 2. The fibers in

the fiber array 10 must also be transmissive throughout the spectral region of operation. In some embodiments, meeting these two conditions requires transmission at wavelengths near or beyond two microns. In such a case, optical fibers made substantially of fused silica are preferred. Low OH⁻ fiber is also preferred because OH⁻ absorption can be confused with glucose absorption in certain spectral regions. In addition, in order to avoid unacceptable confusion among various diffraction orders delivered to the detector array 12, the radiation entering the tissue of the patient can be pre-filtered to block wavelengths shorter than needed for operation of the spectrograph system. Wavelengths longer than required are generally blocked by attenuation in the fiber array 10 as well as by greatly reduced responsivity of the detector array 12, which should be chosen for compatibility with the system's spectral region of operation. The array of optical fibers forming the fiber array 10 can include, for example, ten or eleven fibers arranged along a line oriented perpendicular to a plane extending through the enclosure 8 and parallel to its lid and bottom.

In the present invention, a preferred embodiment employs two identical off-axis sections of a parabolic mirror for the input mirror 2 and the output mirror 4. The center of the input fiber array 10 is at the focus of the input mirror 2 and the center of the detector array 12 is at the focus of the output mirror 4. This arrangement is optimally suited to produce two intersecting regions of substantial collimation from the input mirror 2 and output mirror 4, respectively, in a folded path, one for each of mirrors 2 and 4. The dispersive element 6 is located at or near the intersection of the collimated beam 14 generated by input mirror 2 and the collimated beam 16 incident upon input mirror 4. This is shown more clearly in FIG. 1.

The grating grooves of the dispersive element 6 are substantially normal to the plane of incidence formed by the central rays in collimated beam 14, causing the

dispersion resulting in collimated beam 16 to be substantially parallel to the plane of incidence. In a preferred embodiment, a blazed grating is employed to enhance the diffracted intensity in the desired order of diffraction. The grating is tilted such that the collimated beam in that order corresponding to a desired wavelength near the center of the desired spectral range is centered on the output mirror 4 at or near the optimum off-axis design angle.

As in any spectrometer, the diverging cone-shaped radiation beam 18 from the fiber array 10 should be optically manipulated to cause it to fill or slightly overfill the dispersive element 6 to optimize spectral resolution. In a Czerny-Turner spectrometer arrangement, the need for this type of optical manipulation implies that the input mirror 2 should have approximately the same operational diameter as the dispersive element 6, since the radiation between these components, i.e., beam 14, is collimated. In a preferred embodiment, the input mirror 2 can have an active mirror diameter of 50 mm and the dispersive element 6 can be a square grating having sides 50 mm in length. The off-axis operating angle of the input mirror 2 should be selected to provide sufficient angular deviation to fully separate conical beam 18 and collimated beam 14. For compact packaging, both the angle between the centers of these beams 18 and 14 and the angular cross-section of conical beam 18 should be fairly large, for example, 45°. However, for optimum beam quality and mere fabrication tolerances, both angles should be small. These conflicting requirements are balanced in a preferred embodiment with an angle of about 30° between the beams and a cone size of about 30°-35°. However, other angles are also possible within the scope of the present invention.

The angles discussed above are still so large that a simple spherical mirror for the input mirror 2 and output mirror 4 would have unacceptably large aberrations, resulting in poor optical resolution. Therefore, an off-

axis parabolic mirror section is employed in the preferred embodiment to minimize aberrations. The focal point for the input mirror 2 is located at the center of the fiber array 10 and the off-axis section is chosen to provide the required beam direction for collimated beam 14 parallel to the parabolic axis. The output mirror 4 is chosen to be identical to the input mirror 2 in a preferred embodiment for similar reasons and to provide an image at the detector array through conical beam 20 that is substantially equal in size to the detector array 12 itself.

In addition to the advantages described above, designing the input mirror 2 and output mirror 4 to be identical allows them to be manufactured and used interchangeably, thereby preventing assembly errors and minimizing production tooling and inventory costs. Mechanical mounting means are preferably integral to the rear surface of each mirror 2 and 4. The mounting means are also designed to be identical and to interface with the enclosure 8 in an inversely symmetrical manner. As shown in FIG. 1, the input mirror 2 and output mirror 4 are attached to sidewall 22 of the enclosure 8 and sidewall 22 has elements 22a and 22b which angle inwardly to a mid-portion of sidewall 22 between the input mirror 2 and the output mirror 4. Similarly, dispersive element 6 is attached to sidewall 24 of the enclosure 8 and sidewall 24 is generally opposed to and spaced from sidewall 22. In addition to the above features, additional optical aberration compensation can be achieved in the preferred embodiment by locating the dispersive element 6 further from the input mirror 2 and output mirror 4 than are the fiber array 10 and detector array 12, respectively, located from their associated mirrors 2 and 4. In FIG. 1, this is shown clearly in that sidewall 24 of enclosure 8 holding the dispersive element 6 is located further away from the sidewall 22 holding the input mirror 2 and output mirror 4 than are the sidewalls 26 and 28, to which the fiber array 10 and detector array 12, respectively, are attached.

Because of this location of the dispersive element 6, enclosure 8 has sidewall 30 extending between sidewall 26 and sidewall 24 and sidewall 32 extending between sidewall 26 and sidewall 24. Furthermore, the anamorphic magnification effect of the dispersive element 6, preferably the blazed grating, is used to balance coma and astigmatism at the central wavelength of the operating spectral region. In prior art arrangements, coma and astigmatism were balanced at zero order only.

10 The dispersive element 6 disperses collimated beam 14 from the input mirror 2 into a multiplicity of wavelengths, each diffracted in a slightly different direction. This process forms multiple overlapped beams shown as collimated beam 16, each corresponding to a specific wavelength and direction, and all aimed substantially at the output mirror 4. The output mirror 4 focuses each of the various wavelengths in collimated beam 16 at a slightly different location, forming an extended continuum of overlapping source array images in conical beam 20 directed to the detector array 12.

In a preferred embodiment, the detector array 12 is a multi-element photodetector array, each element of which is substantially taller than it is wide so as to correspond to the shape of each source image. The detector array 12 can be formed of lead sulfide or other semiconducting elements deposited on a substrate. The detector array 12 is oriented with its successive pixels aligned with the image continuum such that each pixel captures a different wavelength region of the continuum. However, to optimize capture efficiency, the plane of the detector array 12 is tilted with respect to the central ray of beam 20 from the output mirror 4 so that a plane common to the elements of the detector array 12 is not normal to the axis of the output mirror's focused beam 20. Rather, the plane of the detector array 12 is oriented such that the astigmatic images formed by the output mirror 4 are elongated in the longer direction of each picture element

(pixel) at and near both ends of the detector array 12. This approach optimizes the concentration of the focused power on each pixel for each associated wavelength and extends the useful angular optical field well beyond that ordinarily associated with reflective optics. In a preferred embodiment, the field of view of the output mirror 4 exceeds $\pm 4^\circ$. In addition, the tilt of the detector array 12 can be between 3° - 20° and in a preferred embodiment is about 10° . The tilt of the detector array 12 also provides the additional advantage that specular backscatter from the detector array 12 is prevented from returning directly back along its optical path. In a preferred embodiment, this tilt angle also exceeds the field of view, thereby forcing such scatter entirely outside that field.

Scattering inside the enclosure 8 is further controlled in a preferred embodiment by designing the orientation angles of the various sidewalls defining the internal surfaces of the enclosure 8 such that there are no grazing-incidence paths that would otherwise direct stray light toward the detector array 12. These are shown in the inwardly directed angle of sidewall 22 and the inwardly directed arrangement of sidewalls 28/32 and 26/30. Furthermore, sidewall 34 extending between sidewall 26 and sidewall 22a and along conical beam 18 is angled outwardly. Similarly, sidewall 36 extending between sidewall 28 and sidewall 22b and along conical beam 20 is also angled outwardly. In addition, a baffle 38 can be located between the input mirror 2 and the output mirror 4 and attached to sidewall 22, in order to prevent undesirable direct illumination of the output mirror 4 by the fiber array 10. Scatter may be further reduced by blackening the inside surfaces of the enclosure 8.

The fiber array 10 and the detector array 12 are preferably mounted in fixed locations on the enclosure with no additional focusing adjustment required. The input mirror 2 and output mirror 4 are each preferably spring-

mounted against the sidewall 22 of enclosure 8 and can be adjusted by a plurality of screws that interface with kinematic features on the rear surface of each mirror. With proper fabrication tolerances on the mirrors 2 and 4, 5 these adjustments will suffice to provide fully adequate pointing and focusing capabilities. Since the dispersive element 6 is in the region of the collimated beams 14 and 16, its location is sufficiently defined by ordinary mechanical tolerances and only angular adjustments must be 10 provided. Several screws can provide azimuth and elevation control, and an eccentric cam on the mount for the dispersive element 6 allows its dispersion plane to be rotated. Azimuth control of the dispersive element 6 permits the central wavelength to be perfectly set at the 15 desired location on the detector array 12. Elevation and rotation control ensure a balanced focus and image-pixel parallelism. The elevation control allows focus equalization from the top to the bottom of each pixel in the detector array 12, while the rotation control allows 20 the plane of dispersion of the dispersive element 6 to be set equally between the two potentially non-coincident planes of incidence.

Having described above the presently preferred embodiments of the present invention, it is to be 25 understood that the invention may be otherwise embodied within the scope of the appended claims.

We claim:

1. A spectrograph suitable for use in the non-invasive sensing of glucose concentrations in the body of a patient, said spectrograph comprising: a collimating input mirror, a focusing output mirror and a dispersive element positioned in an enclosure in a Czerny-Turner type of arrangement, with the input mirror and output mirror attached to a first sidewall of the enclosure and forming a converging means having intersecting regions of substantial collimation located substantially at the dispersive element which is attached to a second sidewall of the enclosure opposite the first sidewall, a fiber array positioned at an input location in said enclosure directing radiation toward said input mirror, with said fiber array carrying radiation from the patient after irradiation with radiation over a predetermined range of wavelengths, a detector array positioned at an output location in said enclosure and oriented to receive radiation from said output mirror, with said detector array including a plurality of photodetector elements and with each element detecting a different wavelength region of the radiation, and with a plane common to the elements of said detector array tilted with respect to a central ray from the output mirror, and with the input mirror and output mirror formed as off-axis, substantially parabolic and substantially identical mirrors.

2. The spectrograph of claim 1 wherein the fiber array is a linear array of optical fibers.

3. The spectrograph of claim 1 wherein the dispersive element is a diffraction grating.

4. The spectrograph of claim 3 wherein the diffraction grating includes equally spaced linear grooves.

5. The spectrograph of claim 3 wherein the diffraction grating is reflective.

6. The spectrograph of claim 1 wherein the dispersive element is a blazed diffraction grating which is tilted such that it provides a preference in intensity for the average angle of diffraction for the wavelength range.

7. The spectrograph of claim 1 wherein the detector array includes a plurality of rectangular pixel elements.

8. The spectrograph of claim 7 wherein the pixel elements are aligned parallel to each other in a linear array.

9. The spectrograph of claim 8 wherein a longer dimension of each pixel element is aligned with that of its neighbor and shorter dimensions of each pixel element lie along two parallel lines common to all pixel elements.

10. The spectrograph of claim 9 wherein the tilt of the detector array is such that images formed away from an optical axis of the output mirror are astigmatic and have an elongation axis substantially in the direction of
5 the long dimension of each pixel element.

11. The spectrograph of claim 1 wherein the input mirror and output mirror each have rear surfaces of the parabolic mirror which are normal to their respective input and output beam axes rather than to their collimated
5 beam axes.

12. The spectrograph of claim 1 wherein the input mirror and output mirror operate in a substantially symmetrical manner to produce magnification substantially at unity.

13. The spectrograph of claim 1 wherein the input mirror, output mirror and dispersive element are attached to the enclosure in a manner permitting adjustment thereof from an exterior of the enclosure.

14. The spectrograph of claim 1 wherein at least one sidewall of said enclosure is angled to direct stray radiation away from the detector array.

15. The spectrograph of claim 14 wherein the first sidewall of said enclosure is angled inwardly in the area generally between the input mirror and the output mirror.

16. The spectrograph of claim 1 further including a baffle within said enclosure and between said input mirror and output mirror and configured to separate radiation incident upon or reflecting from said input
5 mirror and output mirror.

17. The spectrograph of claim 1 wherein the tilt of the detector array is at an angle between 3° and 20°.

18. The spectrograph of claim 1 wherein the tilt of the detector array is at an angle of about 10°.

19. The spectrograph of claim 1 wherein the radiation is in the near-infrared spectral region.

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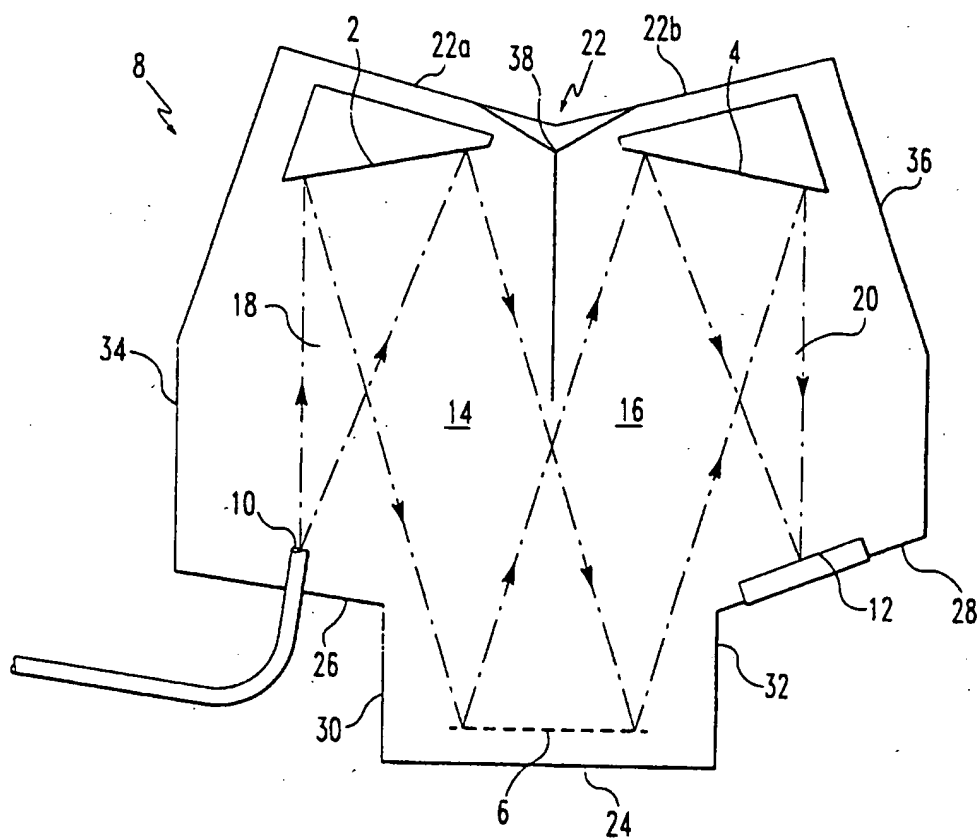


FIG. 1

INTERNATIONAL SEARCH REPORT

International application No.
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A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : A61B 5/00; G01J 3/28

US CL : 128/633; 356/328

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 128/633, 664, 665; 356/39, 326, 328

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,285,596 A (LANDA) 25 August 1981, col.umn 10, line 60 to col. 11, line 23.	1-19
Y	US 4,598,715 A (MACHLER et al) 08 July 1986, co. 5, lines 8-45.	1-14, 17-19
Y	US 5,026,160 A (DORAIN et al) 25 June 1991, entire document.	1-14, 17-19

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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Box PCT
Washington, D.C. 20231Authorized officer
ERIC F. WINAKUR

Facsimile No. (703) 305-3230

Telephone No. (703) 308-3940